AESOP Internal Waves and Boundary Mixing

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LONG-TERM GOALS

This project in collaboration with Eric Kunze at the University of Victoria aims to increase our understanding of (primarily tidal) internal wave processes and how they affect diapycnal mixing in the coastal ocean. An eventual goal is the improved representation of baroclinic tides and mixing parameterizations in numerical models.

OBJECTIVES

- To characterize and understand the horizontal and vertical structure of the internal wave field in a region of coherent but weak internal tides, rough topography, and elevated internal wave continuum.
- To test numerical predictions of internal tide generation and propagation.
- To estimate rates of internal wave spectral energy transfer through critical reflection, topographic generation, and boundary and internal dissipation.
- To estimate bottom boundary layer mixing and its effect on internal wave energy budgets and interior stratification.
- To compare mixing estimates with diffusivities and turbulent fluxes from regional numerical models with a view toward determining the impact of internal waves on simulated distributions of temperature and salinity.
- To use this information to guide improvements in mixing parameterizations, leading to improved predictions of oceanic properties and air-sea fluxes.

APPROACH

Our approach is to combine a tide-resolving survey and timeseries conducted over the continental slope south of Monterey Bay in 2006 (Figure 1) with ancillary mooring and remote sensing datasets from the region (Figure 2) to develop a picture of the 3-D structure of the internal tide and accompanying energy flux and dissipation. Estimates of the along-slope and cross-slope energy fluxes and gradients, together with wavenumber content, provide a test of numerical models predicting topographic generation of internal

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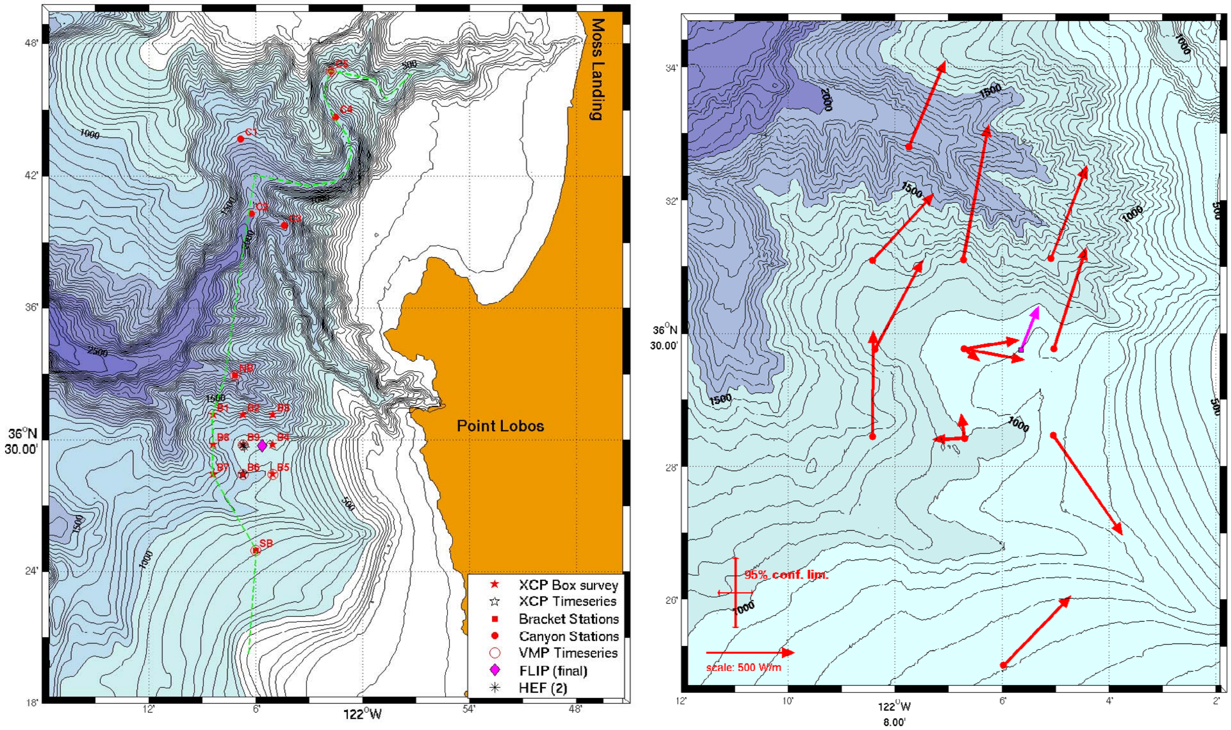

Figure 1: (left panel) Chart showing the locations of timeseries stations occupied over the slope west of Point Lobos and northward into Monterey Canyon during the 2006 profiling survey on the R/V* Point Sur. *Bathymetric contours from a 250m (horizontal) resolution database are shown at a vertical interval of 50m. The green line connecting a south-to-north subset of the stations is used to generate the section shown in Fig.3. (right panel) Enlarged view of the high-resolution survey site near* FLIP. *Bathymetric contours are now from a 40m database. Semidiurnal energy flux vectors from the XCP survey (red arrows) show a generally northward flux of around 500 W/m except at the central, south, and southeastern stations, which show weak or southward flux. The maximum semidiurnal flux from* FLIP *(most comparable to the XCP survey at spring tide) is only about 200 W/m (magenta arrow), but is consistent with an average of the two adjacent stations. 95% confidence limits on the XCP flux estimates (scale bar in lower left corner) are approximately ±200 W/m in the north–south direction, and much less for the* FLIP *estimate.

tides on the continental slope near Monterey Bay. In addition, dissipation and energy flux measurements allow estimates of boundary mixing and spectral transfer through critical reflection.

Profiling instruments used in the 2006 survey on the R/V *Point Sur* included the XCP (expendable current profiler), a rapid-surveying tool providing a full water column (up to 2000 m) profile of temperature and instantaneous horizontal water velocity; VMP (vertical microstructure profiler) a loosely-tethered profiler capable of making hourly profiles of T, S and turbulent dissipation to 1000 m, depending on wind and sea state; EM-POGO, a low-cost free-falling, recoverable, full-water column velocity and temperature profiler; CTD/LADCP (a single 300 KHz Workhorse ADCP mounted on the

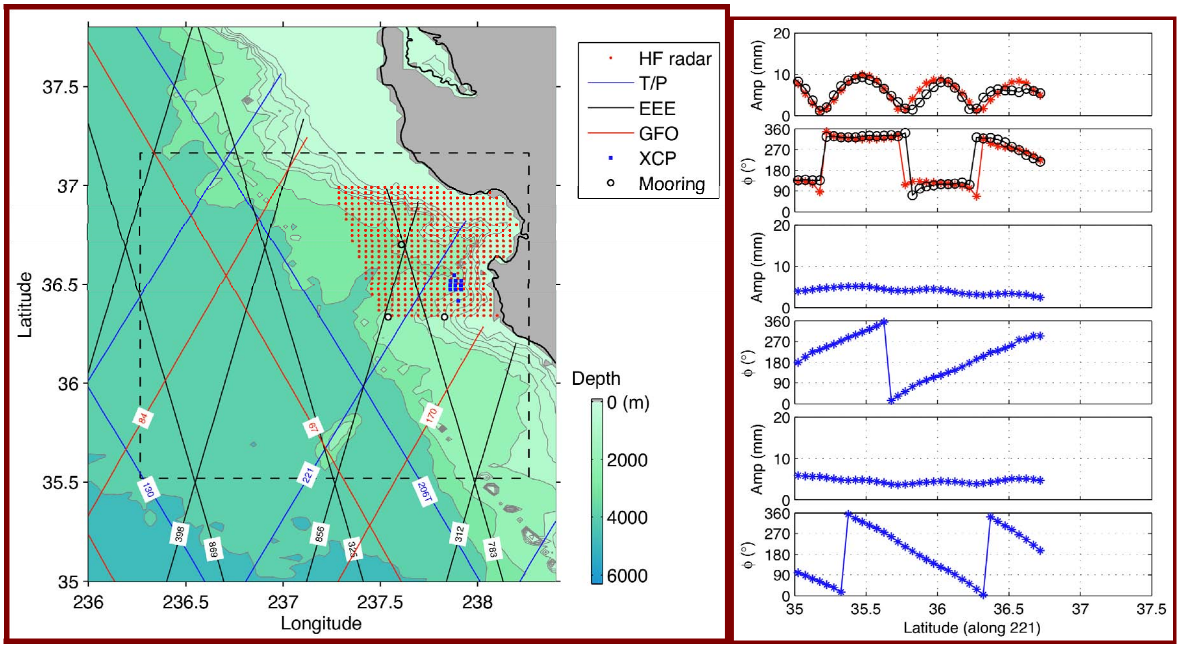

Figure 2: (left panel) Chart showing regional coverage by altimeter (TOPEX/Poseidon, ERS, and Geosat Follow-on satellite tracks), HF Radar, moorings, and the in-situ XCP survey. (right panel) M2 tidal analysis of sea-surface height along TOPEX track 221 shows a standing-wave pattern (top two panels) of alternating high and low amplitude accompanied by 180° shifts in phase. A separation into northward and southward components using the technique of Zhao and Alford (2009) shows 5mm amplitude waves propagating both northeastward (middle two panels) into Monterey Canyon and southwestward (bottom two panels) into the deep ocean.

ship's CTD package), providing full water column measurements of T, S and water velocity, as well as dissolved oxygen, chlorophyll fluorescence, and light transmission; and finally the vessel-mounted 75 KHz and 300 KHz ADCP (acoustic Doppler current profiler), returning profiles of water velocity to 400 m and 100 m, respectively (typically in 5-min averages). In addition the R/P *FLIP* was moored for 16 days near the center of our survey pattern after the survey was completed, providing highly-resolved timeseries of velocity, T and S variability over 80% of the water column. Graduate student S. Brody has been analyzing the profiling survey and FLIP data as part of her Ph.D. research.

Complementary wide-area and long-duration coverage come from satellite altimetry and HF Radar in the region, as well as multi-month moorings deployed west of Point Sur in the 1980s (Tisch et al, 1992). Figure 2 shows the locations of these additional assets. APL Oceanographer Z. Zhao has been working with these datasets, developing filtering techniques for extracting the internal tides (refining and adapting the altimeter methods developed in Zhao and Alford, 2009).

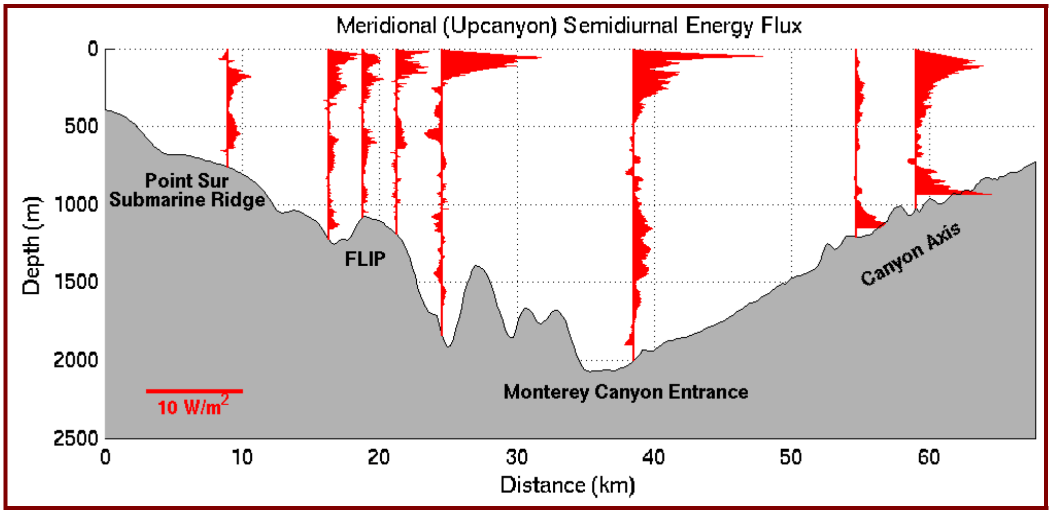

Figure 3: A section along the green line in Fig.1, showing the bathymetry and along-section energy flux profiles from the ridge west of Point Sur (left side), through the survey box around* FLIP*, and up the axis of Monterey Canyon (right side). Energy flux is enhanced in the upper and lower water column due to the overall low-mode internal tide. The more complicated picture in the lower water column near the* FLIP *site is symptomatic of additional local generation.

WORK COMPLETED

The main tasks completed during the past year involved finalizing aspects of the data processing (namely the shipboard ADCP, enabling absolute velocity referencing for the XCP profiles), computing internal wave and mixing-related quantities from the in-situ and remote sensing data (including vertical energy flux and shear spectra from XCPs, horizontal energy flux from the historical moorings via mode fitting, and internal tide characteristics from altimeter and HF Radar), comparing with numerical models, and preparing scientific publications. S. Brody visited Stanford to discuss comparisons with the SUNTANS model run by O. Fringer and D. Kang. A new POM configuration for Monterey Bay has been developed by G. Carter and is also being used for comparison.

RESULTS

Results to date include the following main points:

(1) The energy flux in the semidiurnal internal tide is dominated by the first baroclinic mode, but also has beam-like features which may be tied to critical slopes in the topography (Figure 3). The overall low-mode structure is consistent with a wave generated at the ridge to the south, as suggested by the numerical models.

(2) Despite the overall low-mode character, the depth-integrated energy flux shows significant variability over the 5 km survey region that is not mirrored by the numerical models (Figure 1). The primary candidate for this variability is additional barotropic-to-baroclinic conversion within the region due to rough topography that is not resolved by the models (despite the fact that the models appear to resolve the major features and broad energy flux patterns fairly well).

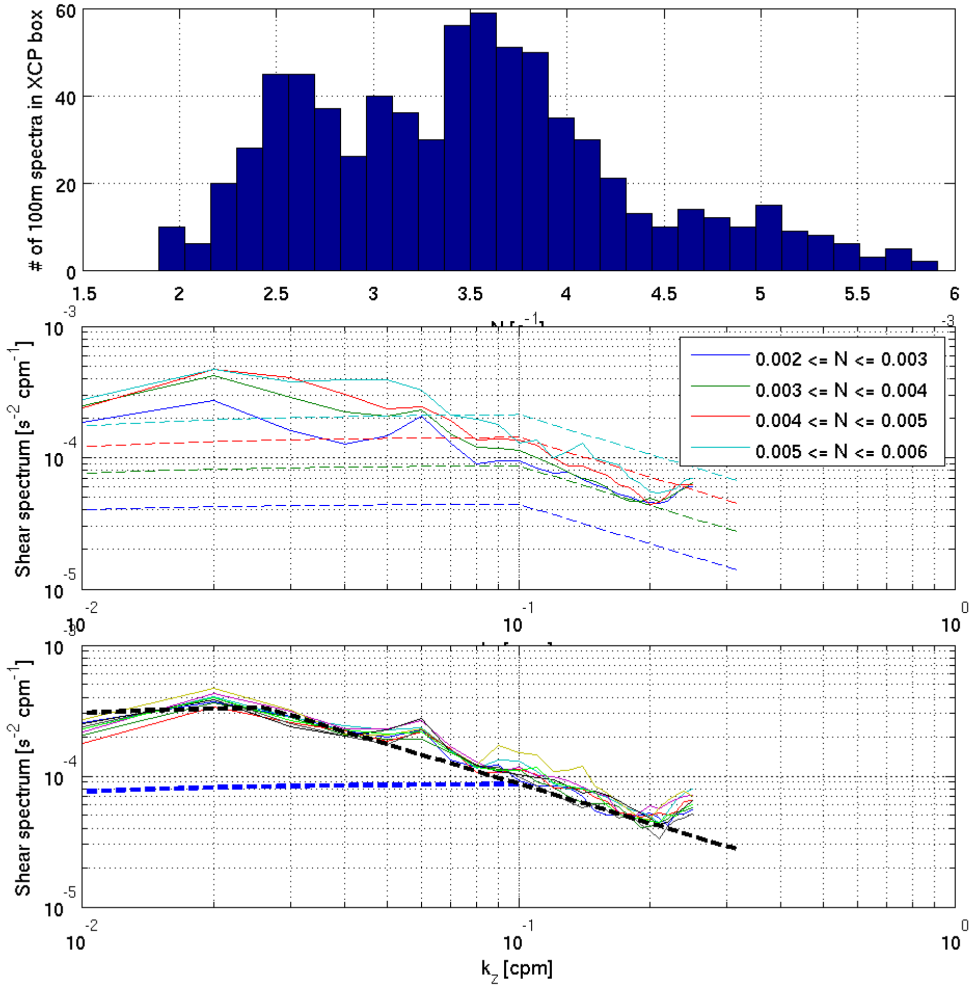

Figure 4: (upper panel) Histogram of buoyancy frequency (*N*) values corresponding to each 100m segment of XCP shear profiles. Most of the values lie between 0.002 and 0.004 s^{-1}, with a scattering of higher values. (middle panel) Solid lines show 100m shear spectra bin-averaged by* N*. Dashed lines show corresponding Garrett-Munk spectra (Gregg and Kunze, 1991). Measured spectra do not scale with* N *as expected, implying relatively higher energy in the lower (less-stratified) part of the water column. (bottom panel) Solid lines show 100m shear spectra averaged over each XCP station in the 3x3 survey. The shapes are very similar from one station to another and agree well with a modified GM spectrum (black dashed line) adjusted to an energy level 4 times higher than the open ocean value (blue dashed line), along with a saturation-range rolloff at a correspondingly lower wavenumber. The peak at 0.06 cpm is believed to be an instrument artifact. GM spectra were plotted with the help of Jody Klymak's Matlab toolbox (http://hornby.seos.uvic.ca/~jklymak/GarrettMunkMatlab/).

(3) Shear spectral shapes are similar to the open-ocean Garrett-Munk (GM) continuum (Figure 4), but with energy levels elevated by about a factor of 4 and the saturation-range rolloff extending to wavelengths as long as 50m (as opposed to 10m for the un-elevated spectrum).

(4) Shear levels scale less strongly with stratification (*N*) than expected for GM, possibly implying bottom generation of short wavelength internal waves.

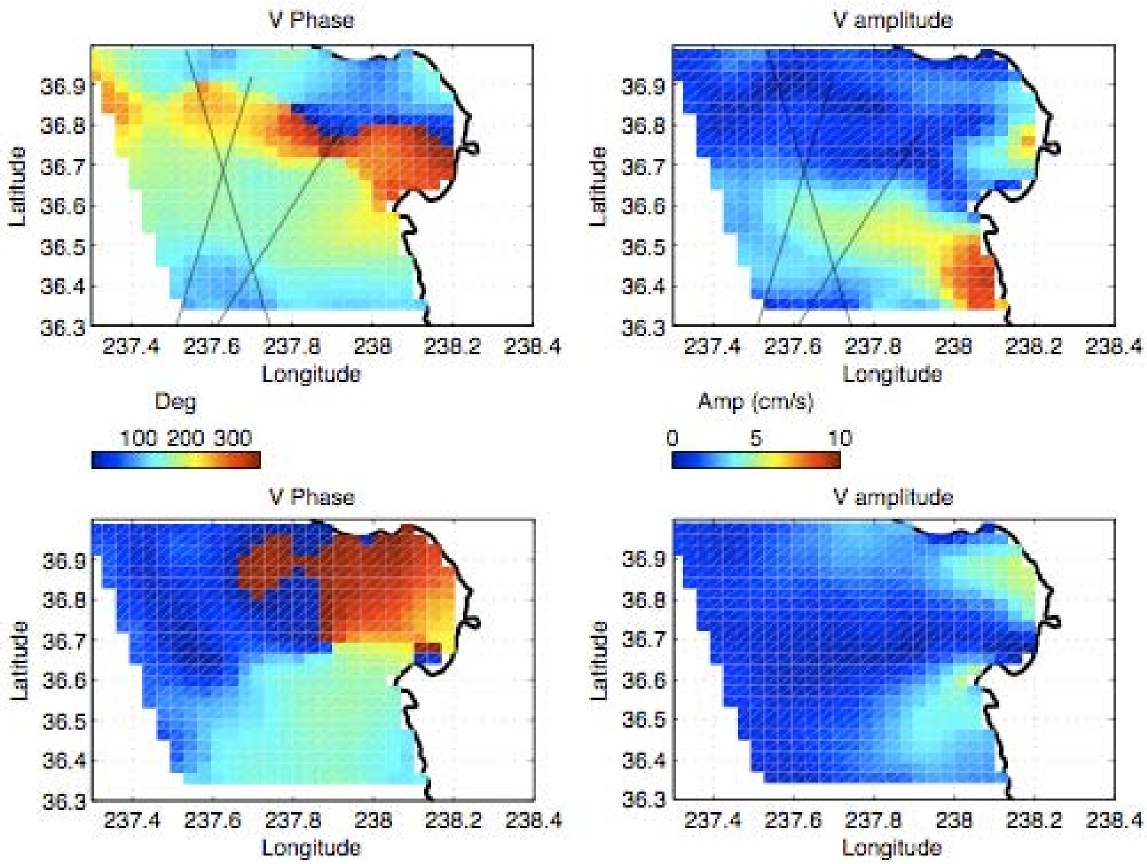

Figure 5: Tidal constituents for north-south component of HF Radar velocity. The upper two panels show M2 (semidiurnal) phase (left) and amplitude (right), revealing an amplitude maximum south of the Monterey Bay and northward phase propagation into the bay, consistent with the northward internal tide in our XCP survey (Fig.1). The lower two panels are the equivalent for the K1 (diurnal) tide, also showing northward phase propagation but a more coastally-trapped amplitude signal, consistent with the expected behavior of sub-inertial waves. The amplitude is significant within the XCP survey region, implying the potential for diurnal contamination of our survey data.

(5) Tidal constituents extracted from altimeter records indicate an overall on-shore baroclinic energy flux all along the central California slope as well as standing wave patterns near the coast (Figure 2). The source of this on-shore flux is not known, but must be included in the regional picture as an additional contribution to the observed internal tide.

(6) Tidal analysis of the HF Radar timeseries is complicated by the fact that it includes both barotropic and baroclinic influences. In fact, according to models (Carter, 2009), even the barotropic tide can have a complicated structure within the bay. Nevertheless, internal tide properties are clearly evident in the tidal constituents (Figure 5). Using spatial filtering it is possible to objectively separate out the mode-1 baroclinic tide, though at the expense of horizontal resolution (Figure 6). This is still work in progress, but could add a valuable new tool to the HF Radar community.

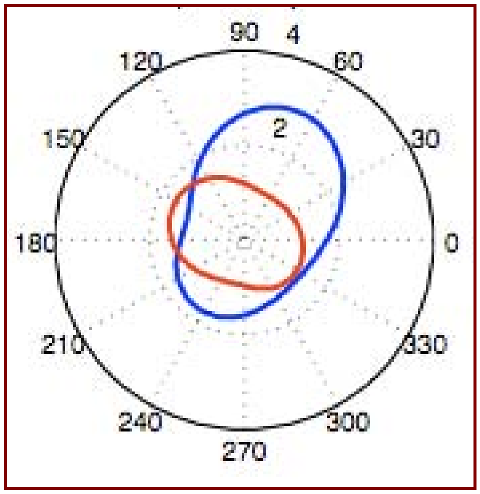

Figure 6: Mode-1 M2 plane wave fit results for HF Radar velocities over the entire Fig.5 domain, following the altimeter techniques of Zhao and Alford (2009). The blue line shows the north-south velocity amplitude as a function of wave direction, and the red line shows the east-west velocity amplitude. Even when applied over the entire region, a north-northeast propagating wave is evident.

(7) Baroclinic tide energy levels at the moorings off Point Sur (Tisch et al, 1992; open circles in Figure 2) are significant, though highly variable, and energy fluxes tend to be weak, as might be expected from measurements directly over a generation site. The moorings are sparsely sampled in the vertical and so can only yield mode-1 internal tide information, but do provide an important check on the spring-neap variability.

IMPACT/APPLICATIONS

Our work is expected to add significantly to the knowledge of the internal wave field, its interactions with topography, and implications for mixing of tracers and momentum. Both the wavefield and the topographic interactions are generally not well-represented in numerical models, resulting in a great degree of uncertainty over appropriate mixing coefficients or parameterizations. Our measurements will permit validation of existing parameterizations in a small highly-resolved region, as well as aid in the development of new parameterizations.

RELATED PROJECTS

Our work has been closely coordinated with the activities of other investigators in the AESOP DRI. In particular, high-frequency measurements from FLIP (Klymak, Pinkel) and regional surveys with SeaSoar (Johnston, Rudnick) help set the temporal and spatial context for our concentrated surveys. Initial results (Jachec et al 2006) from high-resolution modeling efforts by the SUNTANS group (Fringer, Street, Jachec) were instrumental in guiding the final placement of resources in the field program. In the later stages, we have been conferring with these regional modelers on mixing and internal wave validation, as well as with high-resolution process modelers (MacKinnon, Sarkhar, Taylor) on wave-wave interactions and boundary layer processes. In addition, our measurements contributed data to the regional model assimilations being run as part of the ASAP experiment, including NCOM (Shulman), ROMS (Wang) and HOPS (Lermusiaux), and our pre-experiment

planning took advantage of initial results from tide-resolving simulations being run by each of these groups. Recent work has also benefited from synergy with two NSF-sponsored projects in Monterey Canyon: one involving the PI, along with Erika McPhee-Shaw at Moss Landing Marine Labs, and a second project by colleagues Alford, Gregg, and Carter.

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